Bulletin of Glaciological Research 25 (2008) *9–17*

Article

Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India

D.P. DOBHAL[1], J.T. GERGAN[1] and R.J. THAYYEN[2]

1 Glaciology Laboratory, Wadia Institute of Himalayan Geology, 33-GMS Road, Dehradun, 24800, India

2 National Institute of Hydrology, WHRC, Jammu, 180003, India

(Received August 29, 2005; Revised manuscript accepted December 6, 2006)

Abstract

Annual mass balance measurements of the Dokriani Glacier in Gangotri area of Garhwal Himalaya were conducted from 1992–93 to 1994–95 and 1997–98 to 1999–2000. The study was carried out by glaciological method, including weekly measurement of ablation stakes and fixed date measurement of net accumulation. Results of annual mass balance for six years show negative trend with the maximum deficit of $-3.19\times10^6\,m^3$ water equivalent (w.e.) in 1998–99. Annual mean mass balance from 1992–93 to 1999–2000 was $-2.25\times10^6\,m^3\ a^{-1}$ w.e. The resulting $13.54\times10^6\,m^3$ w.e. cumulative volume loss, equal to a thickness reduction of 1.94 m over the study period is significant, since the Dokriani Glacier has average ice thickness of 50 to 55 m. Substantial wasting by -2.5 to -3.0 m w.e. a^{-1} in the ablation area, compared to the mass gain by 0.45 to 0.55 m w.e. a^{-1} in the accumulation area was recorded. Equilibrium line altitude (ELA) has ascended from 5030 to 5095 m a.s.l. and accumulation area ratio (AAR) fluctuated between 0.67 and 0.70 during the study period.

1. Introduction

The Himalaya, on the south of the Tibetan plateau, contains one of the largest concentrations of glaciers and permanent snowfield outside the polar region and influences hydrology and climate of the Indian sub-continent. The low latitude and high altitude orographic characteristics of the Himalaya provide a unique snow/ice and glacier gathering ground for three major river systems in the Indian part of the Himalaya, comprising 3755 glaciers in the Indus basin, 917 glaciers in the Ganga basin and 610 glaciers in the Brahamaputra basin (Geological Survey of India,1999). The distribution of glaciers in the Himalaya is uneven, with higher concentration in the northwest than northeast Himalaya (Vohra, 1981; Geological Survey of India, 1999). This complexity is primarily due to criss-cross topography and variable climatic conditions. This is reflected in the fluctuation of regional snow/firn line ranges from 4500 to 5700 m a.s.l. (Müller, 1958; Mayewski and Jeschke, 1979; Dobhal, 1993; Sharma and Owen, 1996). Glacier mass balance is an important variable in understanding the changes occurring in the glacier regime. It also indicates status and consequences of regional scale climatic changes which will eventually help in the planning and management of water resources of the region.

Himalayan glaciers are difficult to study due to the rugged mountain terrain and harsh weather. Very few studies have been carried out on mass balance of the glaciers situated in the Indian part of the Himalaya. The first mass balance study from the region was reported on Gara Glacier in the Himachal Himalaya (Raina *et al.*, 1977). Since then many other glaciers in the region were studied. However, these studies were restricted for short periods (Singh and Sangewar, 1989; Gautam and Mukherjee, 1989; Dobhal *et al.*, 1995; Bhutiyani, 1999; Srivastava *et al.*, 2001a). Considering this, Dokriani Glacier was taken up for the mass balance studies in 1992. The present study emphasises on annual mass balance of Dokriani Glacier during the period from 1992–93 to 1999–2000 (six years) with the gap of two years (1995–96 and 1996–97).

2. Morphology and climatic setting

Dokriani Glacier (30°50′ to 30°52′N and 78°47′ to 78°50′E) is a well-developed medium size valley glacier with compound basins lying to the southwest of the Gangotri Glacier system in the Garhwal Himalaya (Fig. 1). It is formed by two cirques, one on the northern slope of Draupadi Ka Danda (6000 m a.s.l.) and second on the western slope of Jaonli (6632 m a.s.l.)

which confluence at 4800 m a.s.l. The general flow of the glacier is due NNW for nearly 3.0 km in the higher region and 2.5 km due WNW in the lower area. It flows down from the head for nearly 5.5 km before terminating at 3890 m a.s.l. The altitudinal difference between head and toe is 2100 m with an average gradient of 12°. The glacier occupies an area of 7.0 km^2 out of total catchment area of 15.7 km^2. The maximum thickness of glacial ice is 120 m in accumulation zone and minimum thickness 25 m near the snout area as measured by ground penetrating radar (GPR) profiling (Gergan *et al.*, 1999). The lower part of the glacier is resting over a thick subglacial till layer. Well developed lateral moraines are the prominent glacial features in the valley that demonstrate the past extent of the glacier (Fig. 1).

One third of the ablation area is covered with a thick layer of supraglacial debris. Marginal and transverse crevasses are well developed in the ablation area. Avalanches occur very frequently in the upper ablation area (4600 to 4900 m a.s.l.), where the valley is narrow and bounded by steep rock faces. Above that the valley re-opens into a large accumulation area covering about 68% of the total area of the glacier. Present position of the glacier snout is at 3890 m a.s.l., which is nearly 550 m up stream from its position during 1962 (toposheet mapped in 1962, Survey of India). The Din Gad stream rises from Dokriani Glacier and merges with Bhagirathi River at Bukki (1610 m a.s.l.).

Climate of the area is humid temperate during summer and cold during winter season. There is no previous meteorological data available from the area. Meteorological data was collected at the glacier base camp at 3760 m a.s.l. during the study period. The base camp is located about 1.5 km down from the glacier snout. The main source of precipitation is rainfall that occurs during the summer (June to September) with average of 1000 to 1300 mm at the base camp. Winter precipitation generally occurs between December and March when the western disturbances are dominant in the area as it moves eastward over northern India and maximum snowfall occurs during this period. Although there is no instrumental data on winter snowfall, however, 75 to 150 cm thick snow pack was measured at higher altitudes (5000 to 5100 m a.s.l.) in the early spring in snow pits and probing. In the lower altitudes (4200 to 4000 m a.s.l.) 50 to 25 cm snow depth was measured in the months of April and May, which melt out before the monsoon commences.

Daily mean temperature in summer varies from 17 to −1℃ (May to October) at the base camp. The maximum and minimum monthly mean air temperatures in summer were 11.4℃ in July 1998 and 2.3℃ in November 1999, respectively. Southwesterly wind dominated in summer. Daily average wind speed in months of May and October ranged from 0.55 to 1.94 m s^{-1}. During the remaining months the daily average wind speed ranged from 0.27 to 0.83 m s^{-1}. Mean relative humidity was 57% in May and 80% during June to August. However, September onwards the relative humidity reduced and was closer to the level of May. The slope lapse rate of air temperature within the Alpine catchment was found to be varying between 3.0 and 8.0℃ km^{-1} during summer (Thayyen

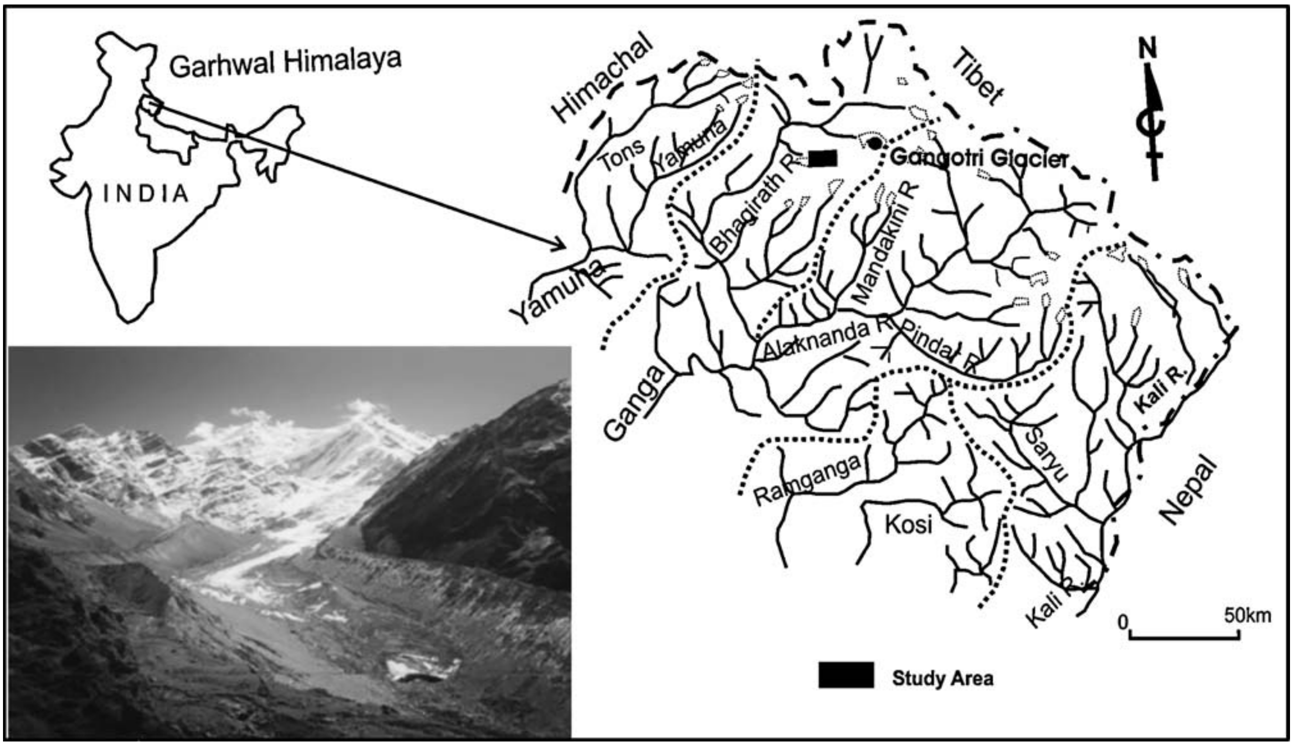

Fig. 1. Map of study area and the frontal view of the Dokriani Glacier.

et al., 2005a). Most of accumulation area was found to be under melting condition as 2℃ isotherm reached near the bergschrund (6000 m a.s.l.) from July to August (Thayyen *et al.*, 2005b). The studies show that the major source of moisture is monsoon in summer and western disturbances in winter, so the area is being influenced by both air circulations.

3. Mass balance measurements

Measurements of mass balance were undertaken by glaciological method with traditional stake network (Østrem and Brugman, 1991). Networks of 22 stakes were placed on the glacier at the end of October 1992. In the following year the number of stakes was increased to 42 (Fig. 2). These stakes were monitored with an interval of 5 to 10 days during the entire ablation period for determining monthly as well as net summer ablation. Accumulation measurements were made in 5 to 6 snow pits at different elevations and by probing of snow thickness in the accumulation area (Fig. 2). The net accumulation was calculated by measuring the residual snow thickness at the end of each ablation season in October. Density of snow pack and ice was measured for various altitude zones. Average densities for snow/firn and ice calculated were 560 and 850 kg m^{-3}, respectively and used for assessing water equivalent.

A large scale map at 1: 10,000 scale, which is made by Survey of India in 1995, with contour interval of 10 m was used to plot mass balance data for each year. Ablation and accumulation data of each stake were plotted on the map and isolines of water equivalent were drawn with an interval of 0.5 m w.e. from snout to accumulation zone. The surface area of each elevation band was calculated by the planimeter and multiplied with the calculated value of net accumulation/ablation of each band to derive the net mass balance of a budget year. October 31 is considered as the end of the budget year for the glaciers. The equilibrium line altitudes are determined by location of the zero valued isoline each year. This provides the basis for the calculation of accumulation area ratio of the glacier for a particular year. As we have adopted the fixed date measurement system (*i.e.* 1 Nov to 31 October) for the annual net balance calculation, year 1993 refers to the budget year 1992–1993.

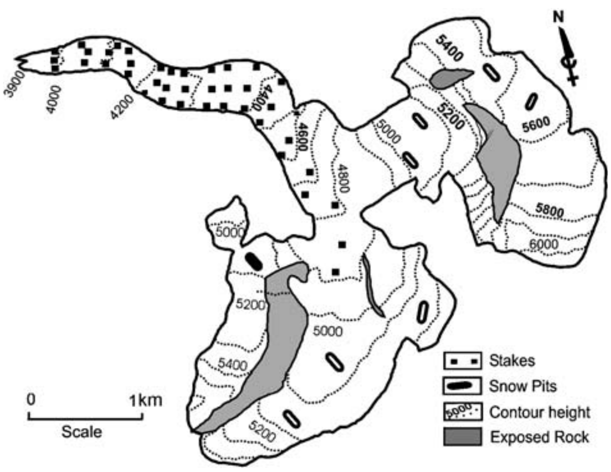

Fig. 2. Map of stake network and snow pits over the Dokriani Glacier.

4. Error estimation

The main sources of error in calculating mass balance by this method are tilting and sinking of stakes on the glacier over a period of time. This may introduce a standard error of 10% in annual mass balance calculation (Tangborn *et al.*, 1975). To reduce such errors all measurements were performed with dense stake networking and were measured with short time interval. However ice density variation and extrapolation for inaccessible crevassed area also add up to the errors. Subsequently, residual snow depth measured by accumulation stakes and identification of the firn line from the snow pits were also considered for error estimation. The resulting error in annual assessment for accumulation measurement ranges from 0.10 to 0.15 m w.e. Estimation of internal accumulation (refreezing) has not been done in the present study. Contribution of avalanches in the higher area also add to the accumulation, beside that extrapolation have been done in higher inaccessible areas which are probably more than 15 to 20% of the total area.

5. Results

5.1 Distribution and profile of mass balance

Detailed mass balance maps of Dokriani Glacier were produced for each year on the basis of field measurement with an interval of 0.5 m w.e. (Fig. 3). The result shows that the pattern of mass balance in accumulation area is nearly consistent every year. The minimum mass balance in accumulation area was recorded in 1999. Consequently the snow line was found at 4800 m a.s.l. in May, while it usually fluctuates between 4000 and 4200 m a.s.l. during the period. The annual average mass balance in the accumulation area was calculated as 0.45 to 0.55 m w.e. a^{-1} for the period from 1993 to 2000. This value is close to the long-term annual average in the accumulation area of 0.43 m w.e. a^{-1} derived from radio-isotopic (^{137}Cs) concentration variation in a shallow ice core from the accumulation area of the Dokriani Glacier by identifying the Chernobyl fallout layer (Nizampukar *et al.*, 2002).

By using stake measurements data of six years, pattern of mass balance in the ablation area was analysed in each 100 m elevation band. In the lower ablation area of the glacier (3900, 4100 and 4300 m a.s.l.),

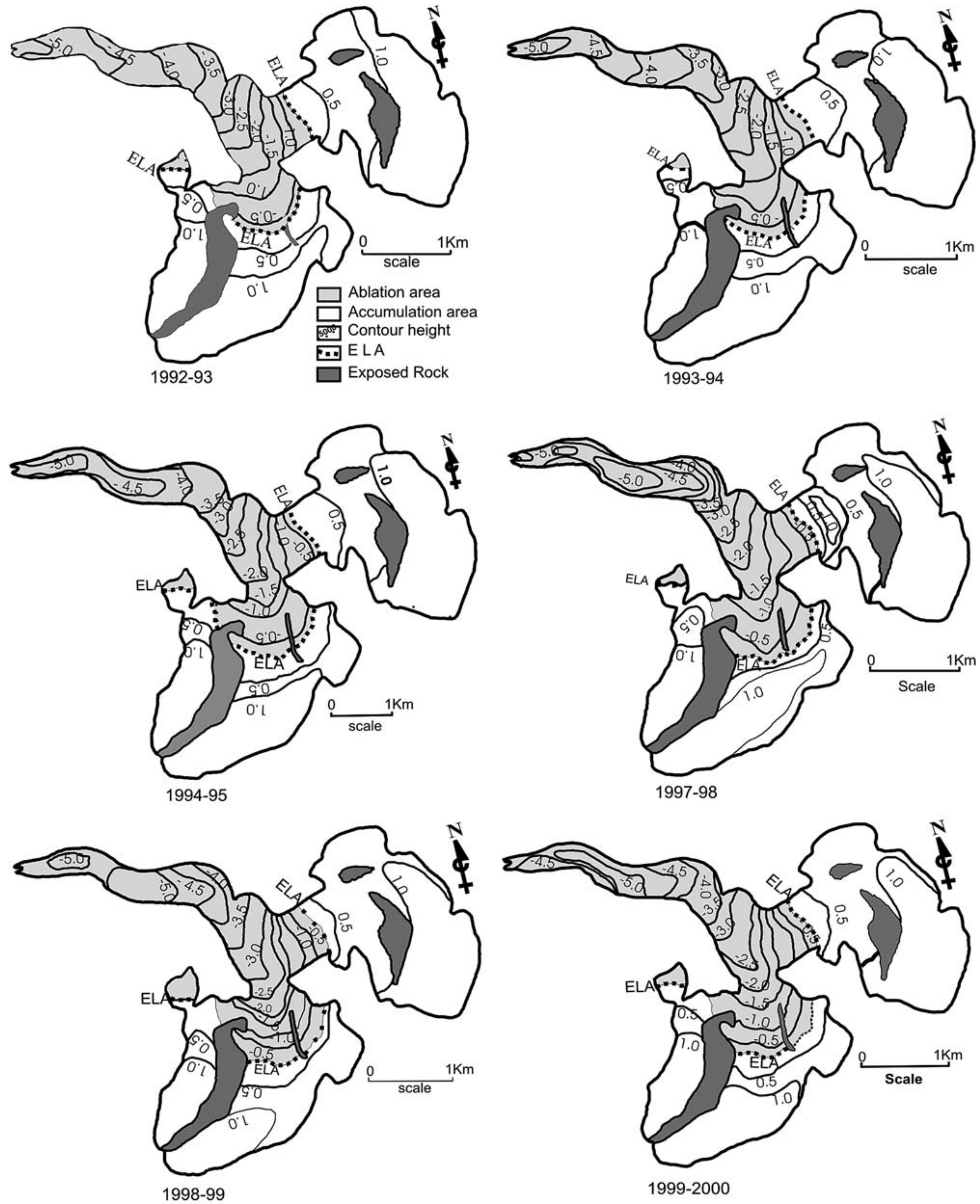

Fig. 3. Annual mass balance maps of the Dokriani Glacier from 1992 to 2000 showing isoline of positive/negative balance at 0.50 m w.e. interval and equilibrium line altitude.

an average was -3.0 to -4.0 m w.e. a^{-1}, whereas -2.0 to -3.0 m w.e. a^{-1} in the higher reaches (4800 to 4900 m a.s.l.). The largest ablation rate was recorded along the central line of the glacier amounting 0.052 m d^{-1} from July to August and the minimum was 0.012 m d^{-1} in October. Daily mean ablation rates during the ablation period for each elevation band between 3900 and 5000 m a.s.l. are plotted in Fig. 4 assuming no snowfall during this period. The result indicates that the ablation rates decrease with increase of elevation. An interesting observation is the changes in the ablation pattern over the years across the ablation area.

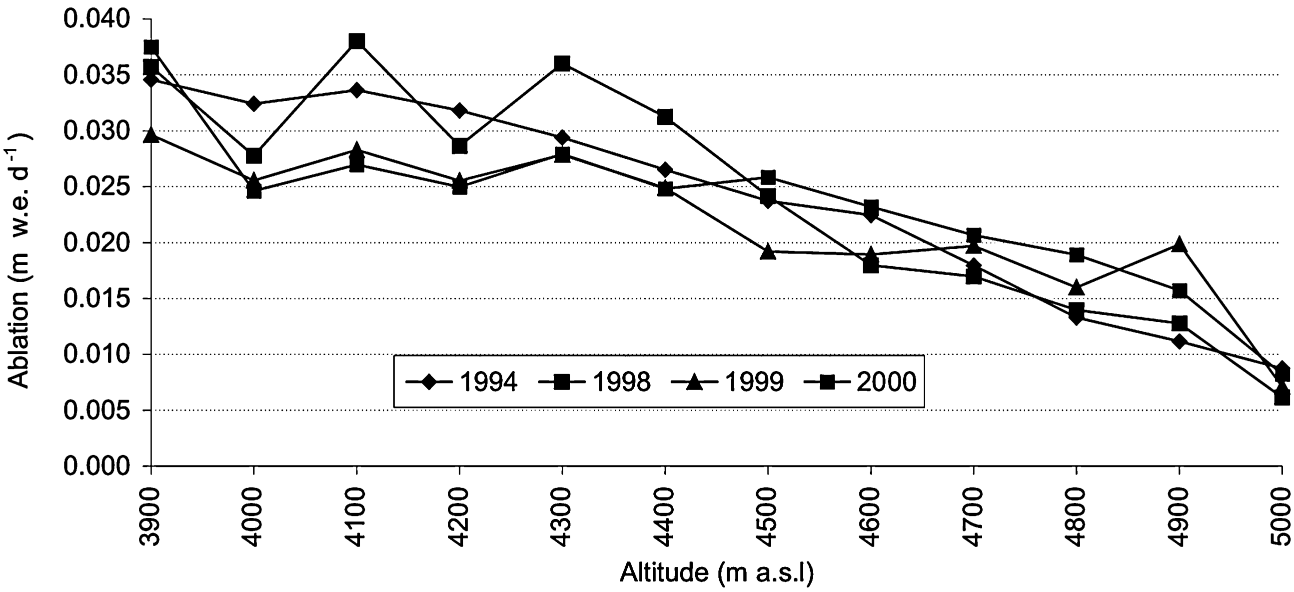

Fig. 4. Daily ablation rates from June to October at different elevations (3900 to 5000 m a.s.l.) of Dokriani Glacier during ablation period of 1994, 1998, 1999 and 2000.

In the lower ablation area (3900 to 4500 m a.s.l.) ablation rate is reducing over the years, whereas they show consistent increase at upper part of the ablation area (4600 to 5000 m a.s.l.). It is also observed that the ablation rate in each elevation band is not always constant during the study period. Ablation was comparatively larger in the lower elevation in 1998 than those in the other years.

Furthermore, altitudinal mass balance profile at interval of 100 m is drawn in Fig. 5. This reveals that the net balance in the ablation area varied for each year. The variability is larger in the lower ablation area and decreases with altitude increase, while the mass balance seems steady in the accumulation area over the period of investigation. The results of mass balances over the period also suggest that the wasting rate of the glacier has been continuously increasing year after year in the ablation areas.

5.2 *Net and specific balances*

Net balance of the glacier is calculated by the integrating values obtained from field measurements between 1992–1995 and 1997–2000 (Table 1). Results of net balance for six years indicate the continuous negative trend with the maximum deficit of $-3.19\times10^6\,m^3$ w.e. in 1998–99. The average net balance of the glacier for six years was $-2.25\times10^6\,m^3$ w.e. a^{-1}, whose average over the entire glacier was -0.32 m w.e. a^{-1}. The specific balance, which is mass balance averaged over the entire glacier, was decreased from -0.22 m w.e. in 1992–93 to -0.38 m w.e. in 1999–2000 with the maximum degradation of -0.46 m w.e. in 1998–99. The study also reveals the substantial mass wasting of glacier in the ablation area by -2.5 to -3.0 m w.e. a^{-1}, compared to the mass gain by $+0.45$ to $+0.55$ m w.e. a^{-1} in the upper reaches of the glacier. In addition the cumulative volume loss by the glacier over the period was calculated as $13.54\times10^6\,m^3$ w.e.

Table 1. Net mass balance of Dokriani glacier for the period 1992–93 to 1999–2000.

Year	Net Balance. ($10^6\,m^3$ w.e.)	Specific balance (m w.e.)	AAR	ELA (m a.s.l.)
1992–93	−1.54	−0.22	0.70	5030
1993–94	−1.58	−0.23	0.69	5040
1994–95	−2.17	−0.31	0.68	5050
1997–98	−2.41	−0.34	0.67	5080
1998–99	−3.19	−0.46	0.66	5100
1999–00	−2.65	−0.38	0.67	5095
Average	**−2.25**	**−0.32**	**0.66**	**5065**

5.3 *Equilibrium line altitude and accumulation area ratio fluctuations*

Equilibrium line altitude (ELA) is the dividing altitude between accumulation area and ablation area, where the annual accumulation equals the annual ablation and is always linked to mass balance of the glacier. ELA of Dokriani Glacier was established by drawing relationship between altitude and mass balance (Fig. 5). Figures 3 and 5 clearly show that the ELA fluctuated between 5030 (1992–93) and 5095 m a.s.l. (1999–2000) during the six years of measurement. Computed ELA positions coincided with the field observations, which were mapped every October during the study period. The ascending trend of ELA during successive years shows that accumulation area of the glacier is reducing. The ELAs and specific balances for six years (Fig. 6a) show good correlation ($r^2=0.91$) suggesting that the ELA responds to the glacier mass fluctuation instantaneously without any lag. The linear regression analysis shows that the

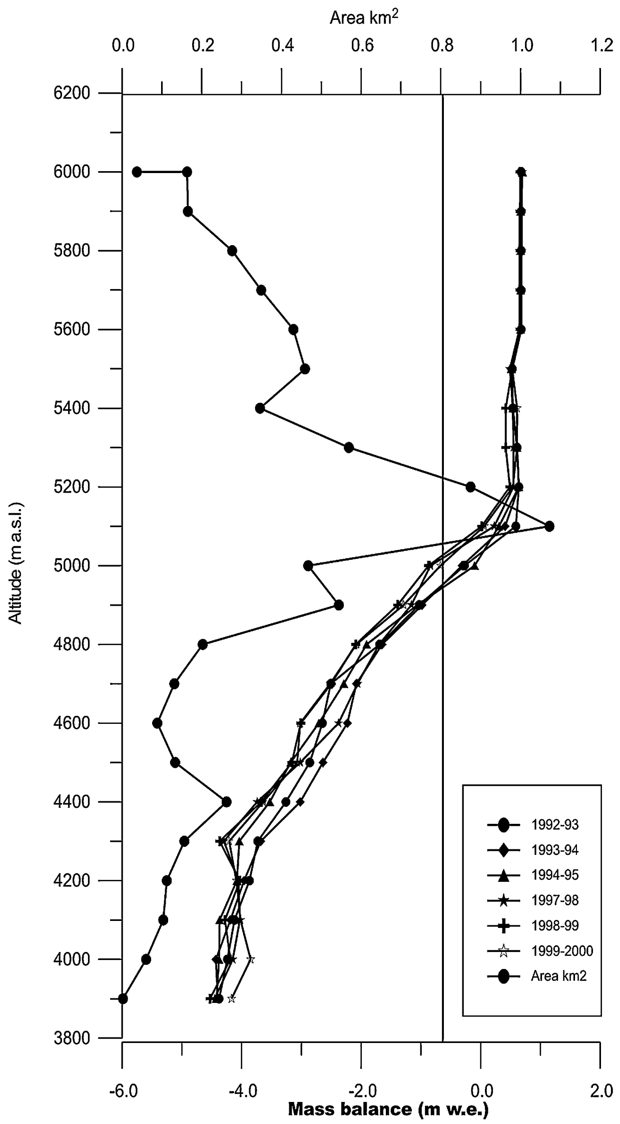

Fig. 5. Altitude versus mass balances and area distribution of the Dokriani Glacier.

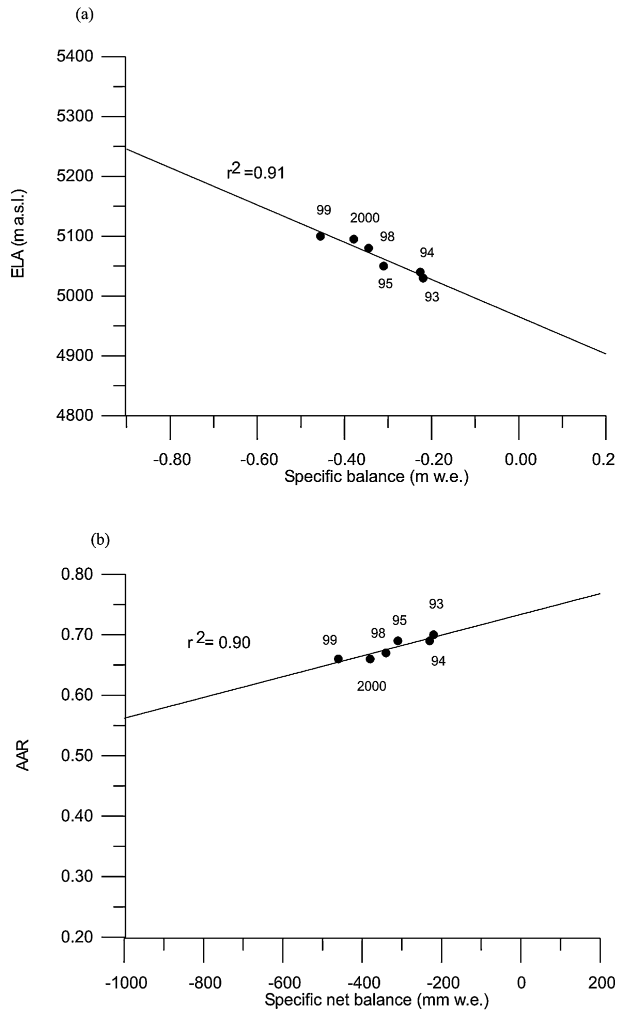

Fig. 6. Relationship between specific balance and equilibrium line attitude (ELA) (a), and accumulation area ratio (AAR) (b) of Dokriani Glacier. The ELA and AAR for equilibrium state of the glacier are obtained to be 4965 m a.s.l. and 0.73, respectively.

mass balance of the glacier could achieve equilibrium with the ELA at 4965 m a.s.l.

Accumulation area ratio (AAR) is the ratio of accumulation area to the entire area of the glacier (Meier, 1962). The AAR of the Dokriani Glacier varied between 0.70 in 1992–93 and 0.66 in 1999–2000. The decreasing trend of the AAR indicates the decrease in accumulation area and increase of ablation area. The regression analysis between specific balance and AAR (Fig. 6b) shows good correlation ($r^2=0.90$). Meier and Post (1962) suggested an AAR of 0.58 corresponding to zero mass balance for the North Cascade Glaciers. Paterson (1981) suggested an AAR of 0.7 for zero mass balance for the alpine glaciers. The mass balance studies on glaciers in Himachal and Garhwal Himalaya (Gautam and Mukherjee, 1989; Singh and Sangewar, 1989; Srivastva and Swaroop, 1989; Dobhal, 1993) suggest that the glaciers experiencing positive mass balance regime have the AAR of 0.7 or more while the AAR is less than 0.7 under the negative balance regime. For Dokriani Glacier AAR of 0.73 corresponds to equilibrium state of the glacier.

6. Discussion

The mass balance showed obvious degradation of Dokriani Glacier through the six years of observation. It was also observed that the characteristics of winter precipitation significantly influence the annual mass balance, as winter snowfall provides the major input to the accumulation of this glacier. During the winter of 1998–99 little snowfall was reported (Table 2) and the highest negative balance was recorded in the following summer. Reduced winter precipitation leads to longer time of exposure of glacier ice for melting as well as reduced accumulation leading to higher mass loss from the glacier. The enhanced rate of mass depletion by −0.22 in 1992–93 and −0.38 m w.e. in 1999–2000 indicates greater percentage contribution of glacial degraded runoff in bulk discharge. Glacier degradation by terminus recession during the study period between 1991 and 2000 resulted in 161.15 m with average rate of 17.9 m a^{-1}.

The cumulative ice volume loss of Dokriani Glacier since 1962 was estimated to be $70.11\times10^6\,m^3$ w.e. with an average of $2.12\times10^6\,m^3$ w.e. a^{-1} (Dobhal *et al.*, 2004), which is very close to the annual mean mass loss of the glacier $2.25\times10^6\,m^3$ w.e. a^{-1} measured in this study. This suggests that over a period of three decades the glacier has been losing its mass at the same rate. As a result of this cumulative mass loss from the glacier over the last 33 years, average ice thickness of Dokriani Glacier reduced from 55 m in 1962 to 50 m in 1995 (Gergan *et al.*, 1999). The length of the glacier decreased by 550 m from its position marked in 1962 to 1995 (Toposheet in 1962 and 1995, Survey of India) with an average rate of retreat as 16.6 m a^{-1}. Frontal area vacated during the three decades was about 10% of the total area of the glacier during the same period (Dobhal *et al.*, 2004). This shows highly responsive nature of medium sized Central Himalayan glaciers to the negative mass balance regime and climate change, probably resulted from lesser precipitation in winter as well as higher ablation in summer.

Across the Himalayan arc glaciers are wasting their mass and the region has very limited mass balance studies to quantify this shrinkage. Mass balance data of ten glaciers from different regions of the Himalayas for different time spans between 1975 and 1990 is being analysed (Fig. 7 and Table 3). Mass balances of these glaciers were estimated by the glaciological method. The investigation periods of most glaciers were 7 to 10 years except for Chhota Shigri and Ruling Glaciers having only two years of measurement. Data suggested that the trends of annual specific balance for these glaciers were strongly negative throughout the observation periods with exceptions of positive balance in 1975, 1976 and 1982. However, continuous negative trend of specific balance have been observed since 1984 (Fig. 7). The annual mean specific balances of theses glaciers were ranging between −105 and −1038 mm w.e. a^{-1} as compared to −320 mm w.e. a^{-1} for Dokriani Glacier during the study period.

Relating mass balance fluctuations to meteorological conditions for the Himalayan glaciers is more complicated due to high climatic variability in the region. The Himalaya forms the southern limits of the Tibetan Plateau. Glaciers occupy between 4000 and 7000 m a.s.l. of the Himalaya and have an enormous influence on the natural environment of its adjoining regions. The high plateau causes many changes in the atmospheric column, such as differential heating effect which is low near the plateau and high above it. It intercepts the sub-tropical planetary high-pressure zone and has a direct effect on the Indian monsoon (Li and Xu, 1984). Vohra (1981) suggested that the Ganga basin (Central Himalaya) experienced equal amount of summer precipitation from monsoon and winter precipitation from western disturbances. The climate of the glaciated region of Central Himalayas is influenced by summer monsoon precipitation. The monsoon rain starts around mid-June and continues till the end of September. Monsoon ensures a higher temperature regime on the mountain with the release of latent heat of condensation (Thayyen *et al.*, 2005a). Precipitation in the form of snow occurs from November to March and sometimes continues up to mid-April. Climate of the Himalayan regions has been poorly studied, especially at higher altitudes. The meteorological data collected during four summer observation years at the study

Table 2. Monthly Precipitation (rainfall), monthly mean temperature and winter snowfall recorded at base camp meteorological station (3760 m a.s.l.) and altitude of snow line in May of Dokriani Glacier.

Parameters	Precipitation (mm w.e.)				Temperature (℃)			
Months	1994	1998	1999	2000	1994	1998	1999	2000
May	—	09	97	68	—	9.4	6.8	9.1
June	115	193	171	265	12.5	10.0	8.7	9.3
July	500	212	304	555	11.4	11.4	10.8	10.2
August	457	353	225	269	10.7	10.9	10.1	10.5
September	190	240	225	146	9.7	8.7	8.7	7.5
October	26	232	—	10	5.5	5.3	—	6.1
Total	1289	1243	1098	1314				
Winter precipitation (mm w.e.)	500	450	144	210				
Altitude of snow line in May (m a.s.l.)	3500	3700	4800	4000				

Table 3. Specific balances of Himalayan glaciers.

Name of glacier	Period of observation	Specific balance (mm w.e. a^{-1})	Area km^2	Elevation Range (m a.s.l.)	Region	Orient-ation	Reference
Neh Nar	1976–1984	−535	1.24	3920–4925	Kashmir	N	1
Ruling	1980–1881	−105	0.947	5680–6050	Ladak	N	2
Gara	1974–1983	−324	5.19	4750–5600	Himachal	NE	3
Gor Garang	1976–1985	−572	2.02	4750–5400	Himachal	SW	4
Shaune Garang	1984–1989	−407	4.94	4350–5360	Himachal	W-N	5
Chhota Shigri	1987–1988	−154	8.75	4050–5600	Himachal	N	6
Dunagiri	1984–1990	−1038	2.56	4200–5250	Uttaranchal	NW	7
Tipra Bank	1981–1988	−241	7.0	3800–5600	Uttaranchal	NW	8
Dokriani	1993–2000	−320	7.0	3900–6000	Uttaranchal	NW	9
Changme Khangme	1979–1986	−298	4.5	4850–5650	Sikkim	S	10

1. Srivatava *et al.*, 1999; 2. Srivastava *et al.*, 2001b; 3. Raina *et al.*,1977; 4. Ravi Shanker, 2001; 5. Singh and Sangewar, 1989; 6. Dobhal, 1993; 7. Srivastav and Swaroop, 1989; 8. Gautam and Mukherjee, 1989; 9. Present work; 10. Sharma *et al.*,1999.

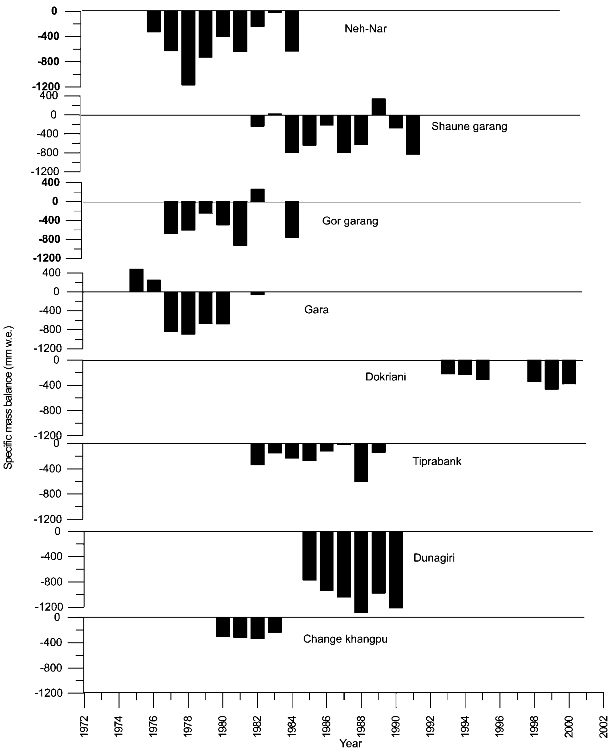

Fig. 7. Annual specific balances of glaciers in Indian Himalayas. Location and observation period are summarised in Table 3.

site (3760 m a.s.l.) has been summarised in the Table 2. The data suggests that higher monthly mean temperature in 1994 and 1998 rather than in 1999 and 2000. Rainfall recorded during the period ranges between 1098 and 1314 mm. It was observed that greater area of glacier catchment experienced rainfall in 1999 and 2000 as compared to 1994 and 1998. This variability is due to the (as indicated by the) major shift in two degree isotherm to the higher altitude during the study periods (Thayyen *el al.*, 2005a). Winter snow cover and its duration play an important role in determining the temperature distribution over the glacier in summer. Reduced snow cover result in more homogenous warming in the higher altitude, due to lower albedo for a longer period leading to a warmer glacier regime and reduced lapse rate. Thayyen *et al.* (2005b) demonstrated that the warmer glacier regimes in summer months of 1999 and 2000 as compared to 1994 and 1998, even when the temperature measured at base camp show higher temperatures in 1994 and 1998. July and August months experienced higher temperatures as well as high monsoon rainfall. The study also suggests that lower lapse rates in 1999 and 2000 may be the result of reduced distribution of snow cover in the glacier catchment as indicated by the snow line altitude in the beginning of summer observation in May (Table 2) even while experiencing reduced temperatures as observed in the year 1999 and 2000.

7. Conclusions

Annual net balance of the Dokriani Glacier investigated since 1992–93 showed continuous negative trend with the maximum deficit of $-3.19\times10^6\,m^3$ in 1998–99. Mean glacier degradation since 1992–93 was found to be -0.32 m w.e. a^{-1}. The vertical mass balance gradient has increased over the period of study, indicating an increase of ablation below the ELA and decreasing of the snow accumulation above the ELA. In addition, the study of annual specific balances of ten glaciers during the period from 1975 to 1990 (Table 2) reveals that all the glaciers have experienced negative balance ranged from -105 to -1038 mm w.e. a^{-1}. This pretends that the Himalayan glaciers are actively under degradation phase like the other glacier in the world.

The study of mass balance pattern shows that the annual mean ablation rate ranges between -2.5 and -3.5 m w.e. a^{-1}, while annual mean accumulation rate was 0.45 m w.e. a^{-1} during the study period in the 1990s.

Within the ablation area enhanced ablation in the upper ablation portion and reduced ablation of lower portion were observed. The continuous negative net balance, retreat of frontal snout, ascending ELA and reducing AAR of Dokriani Glacier supports that the active degradation phase is going through at present.

Acknowledgment

We are thankful to the Director, Wadia Institute of Himalayan Geology (WIHG), Dehra Dun for encouragement and providing the necessary facilities to carry out this work. Financial assistance provided by Department of Science and Technology, Ministry of Science of Technology, New Delhi (Government of India) is thankfully acknowledged. We are also grateful to Dr. Bernard Francou, IRD, Bolivia and an anonymous reviewer for their critical comments and suggestions to improve the paper.

References

Bhutiyani, M.R. (1999): Mass-balance studies on Saichen glacier in Nubra valley, Karakoram Himalaya, India. J. Glaciol., **45** (149), 109–118.

Dobhal, D.P. (1993): Inventory of Himachal glaciers and glaciological studies of Chhota Shigri glacier, Himachal Pradesh: a case history. Unpublished Doctoral thesis, Wadia Institute of Himalayan Geology Dehra dun, 266pp.

Dobhal, D.P., Gergan J.T. and Thayyen, R.J. (2004): Recession and morphogeometrical changes of Dokriani glacier (1962–1995) Garhwal Himalaya, India. Current Science, **86** (5), 692–696.

Dobhal, D.P., Kumar, S. and Mundepi, A.K. (1995): Morphology and glacier dynamics studies in Monsoon arid transition zone: An example from Chhota Shigri glacier, Himachal Himalaya, India. Current Science, **68** (9), 936–944.

Gautam, C.K. and Mukherjee, B.P. (1989): Mass-balance vis-à-vis snout position of Tipra bank glacier District chamoli, Uttar Pradesh. Proceedings of National Meet on Himalayan Glaciology, 5–6 June 1989, 141–148.

Geological Survey of India (1999): Inventory of the Himalayan glaciers. A contribution to the International Hydrological Program (M.K. Kaul, Ed.), Geological Survey of India, Special. Publication no. **34**, 165 pp.

Gergan, J.T., Dobhal, D.P. and Kaushik, R. (1999): Ground penetration radar ice thickness measurement of Dokriani Bamak (Glacier), Garhwal Himalaya. Current Science, **77** (1), 169–174.

Li, J. and Xu, S. (1984): The distribution of glaciers on the Qinghai-Xizang plateau and its relationship to atmospheric circulation. *In:* Miller, K.J. (Ed). *The International Karakoram Project, Proceeding of the International Conference, Cambridge, Cambridge University Press,* **1**, 84–93.

Mayewski, P.A. and Jeschke, P.A. (1979): Himalayan and Trans Himalayan glacier fluctuation since AD 1812. Arctic and Alpine Research, **11** (3), 267–287.

Meier, M.F. (1962): Proposed definition for glacier mass budget terms. J. Glaciol., **4** (33), 252–263.

Meier, M.F. and Post, A.S. (1962): Recent variation in mass net budgets of glacier in North America. International Association of Scientific Hydrology, Publication no. **58**, 63–77.

Müller, F. (1958): Eight month of glacier and soil research in the Everest region. In: The Mountain World, New York, 191–200.

Nizampurkar, V., Rao, K., Sarin, M. and Gergan, J.T. (2002): Isotopic study on Dokriani Bamak glacier, Central Himalaya: Implication for climate changes and ice dynamics. J. Glaciol. **48** (160), 81–86.

Østrem, G. and Brugman, M. (1991): Glacier mass balance measurements: A manual for field and office work, Science Report-4. National Hydrological Research Institute, Saskatoon/Norwegian water recourse and electricity board, Oslo, 224pp.

Paterson, W.S.B. (1981): The physics of glaciers. Second edition, Oxford University, Pergamon Press, 380 pp.

Raina, V.K, Kaul, M.K. and Singh, S. (1977): Mass balance studies of Gara Glacier. J. Glaciol. **18** (80), 415–423.

Ravi Shanker (2001): Glaciological studies in India; contribution from geological Survey of India. Proceeding of Symposium on Snow, Ice and Glacier, March 1999, Geological Survey of India Special Pububublication no. **53**, 11–15.

Sharma, M.C. and Owen, L.A. (1996): Quaternary glacial history of NW Garhwal, Central Himalayas. Quaternary Science Review, **15**, 335–365.

Sharma, S and 10 others (1999): Mass balance studies of Changme Khangpu glacier, Mangan District, Sikkim. Symposium on Snow, Ice and Glacier, March 1999, Abstract, 10–11.

Singh, R.K. and Sangewar, C.V. (1989): Mass balance variation and its impact on glacier flow movement at Shaune Garang glacier, Kinnaur, Himachal Pradesh. Proceedings of National Meet on Himalayan Glaciology, 5–6 June 1989. 149–152.

Srivastava, D. and Swaroop, S. (1989): Fluctuation of Dunagiri Glacier, District Chamoli, UP. Proceedings of National Meet on Himalayan Glaciology, 5–6 June 1989, 153–156.

Srivastava, D., Sangewar, C.V., Kaul, M.K. and Jamwal, K.S (2001a): Mass balance of Ruling Glacier- a Trans-Himalayan glacier, Indus basin, Ladak. Proceeding of Symposium on Snow, Ice and Glacier, March 1999, Geological Survey of India, Special Publication. **53**, 41–46.

Srivastava, D., Swaroop, S., Mukerji, S., Roy, D. and Gautam, C.K. (2001b): Mass balance of Dunagiri Glacier, Chamoli District, Uttar Pradesh. Proceeding of Symposium on Snow, Ice and Glacier, March 1999, Abstract, 10–11.

Tangborn, W.V., Krimmel, R.M. and Meier, M.F. (1975): A comparison of glacier mass balance measurements by glaciologic, hydrologic and mapping methods, South Cascade Glacier, Washington. In; Proceedings, International Association of Hydrological Science, Moscow General Assembly, U.S.S.R., 1971: IAHS-AISH Publication, **104**, 185–196.

Thayyen, R.J., Gergan, J.T. and Dobhal, D.P. (2005a): Slope lapse rates of temperature in Din Gad (Dokriani Glacier) catchment, Garhwal Himalaya, India. Bulletin of Glaciological Research, Japanese Society of Snow and Ice, **22**, 31–37.

Thayyen, R.J, Gergan, J.T. and Dobhal, D.P. (2005b): Monsoonal control on glacier discharge and hydrographic characteristics, a case study of Dokriani glacier, Garhwal Himalaya, India. J. Hydrol., **36** (1–4), 37–49.

Vohra, C.P. (1981): Himalayan glaciers. In: Himalayan aspects of change, Lall, J.S. and Maddie, A.D. (Ed.), Oxford University Press, Delhi, 138–151.